Process-oriented diagnosis of tropical cyclone genesis and intensification in high-resolution global models

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Abstract

Despite recent improvements, many global climate models (GCMs) still show strong biases in the representation of tropical cyclone (TC) activity, especially its frequency and intensity. These GCM biases limit the reliability of TC sub-seasonal and seasonal predictions and future projections. A lack of diagnostics that could provide insights into process-level errors in the model representation of TCs has slowed model improvement.

We propose a project focused on the diagnosis of process-level errors in the model representation of TC genesis and intensification. Our proposed project will build upon the success of our ongoing project, during which we have developed process-oriented diagnostics for TCs by adapting diagnostics that were originally developed for the Madden-Julian Oscillation (MJO) and convective self-aggregation. No widely-accepted such process-based diagnostics for global TC modeling existed before our current project. The diagnostics we developed have been applied to a limited number of high- and low-resolution GCMs, which has allowed us to identify processes that are key to TC intensification and genesis. In the proposed work, we will extend the development and implementation of these diagnostics so that they may be fully utilized as a community tool and may guide NOAA model development:

- First, we will examine key processes associated with TC genesis and intensification in long term satellite observations and reanalysis products, using multiple observations to quantify uncertainty. This will provide a “reference” version of our diagnostics against which the model representation of the same processes can be validated. This process-level evaluation against observations is crucial to model improvement.
- Second, while the diagnostics developed have been applied to a limited number of model simulations that have been obtained in an opportunity-based manner, the diagnostics and comparison with observational results need to be applied to a wider group of models. We will take advantage of the upcoming model intercomparison projects (CMIP6/HighResMIP/PRIMAVERA) to evaluate and identify biases in the model simulations;
- Third, we will use the new NOAA model (GFDL AM4/CM4), which has been already developed and shows decent capability in simulating TCs globally, to perform targeted experiments guided by the results of our ongoing project and the proposed observational analyses. The result of the targeted simulations will help improve the NOAA model, and also would provide useful information to other modeling groups;
- Lastly, we will translate the existing codes and scripts to open source languages and implement it into the NOAA MDTF diagnostics package to maximize the accessibility of the diagnostics.

This project fits well within the MAPP Competition entitled “Addressing Key Issues in CMIP6-era Earth System Models”, by developing and using process-oriented diagnostics to identify the source of GCM biases in TC simulation and by providing paths toward the model improvement. This advancement in our understanding of TC simulation will be extremely valuable for improving the next generation of

climate models, which is vital for making robust projections of future TC activity and its impacts; a key component of NOAA’s long-term goals.

Advancing understanding of Arctic sea ice variability and diagnostic predictability in ESMs with regional-to-global-scale process- oriented evaluation

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Abstract

In this proposal for MAPP Competition 2, Addressing Key Issues in CMIP6-era Earth System Models, we propose to characterize and understand biases in CMIP6 Arctic sea ice variability. We will focus on determining relationships between modeled quantities that are observable and quantities that characterize processes, so that we can simultaneously evaluate an observable and sea ice processes. We seek to understand when biases are due to missing physics or poor tuning and what makes some models outliers. We will use this understanding to recommend essential model physics and future directions in sea ice modeling.

The objectives of this proposal focused on creating metrics are threefold. (1) Categorize the spatial and temporal nature of sea ice variability across the multi-model ensemble, in both the unforced intrinsic variation and forced response. This will give us a basis from which to evaluate the role of ocean-ice and atmosphere-ice processes on the sea ice. (2) Characterize the spatio-temporal variability of atmosphere-ice and ocean-ice interface fluxes associated with sea ice variability (3) Quantify ocean stratification strength, the amplitude and vertical structure of atmospheric meridional energy fluxes into the Arctic and radiative variability associated with clouds and sea ice and how each impacts sea ice variability.

We will develop process-oriented metrics in order to understand inter-model spread in the drivers of sea ice variability and to place the models in the context of observations. The metrics are designed to identify parameterizations and model physics that need improvements. We will test proposed improvements in the developmental Community Earth System Model (CESM) and work with the CESM working groups to communicate necessary changes to other climate model developers.

We are enthusiastic about working with the NOAA Model Diagnostics Task Force (MDTF) to create new process-oriented analysis scripts and will contribute our analysis scripts and abide by their coding requirements. Our analysis tools will be designed to run on generic CMIP6 output formats. We also plan to work with our NOAA GFDL collaborator Dr. Mitch Bushuk, participants of the Sea Ice Prediction Network, and participants in the Sea Ice Model Intercomparison Project (SIMIP) as outlined in the proposal.

Understanding the Role of Radiative Forcing and Cloud-Circulation Feedbacks on Spatial Rainfall Shifts in CMIP6

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Abstract

A robust prediction of all climate models is for *wet regions to become wetter* and *dry regions to become drier* in response to increased greenhouse gases. The physical processes that drive this response arise from increased water vapor and are generally considered to be well understood. In contrast, the processes that govern *spatial shifts* of rain belts are less well understood, despite the fact that such changes also have profound societal consequences. This is particularly relevant in the tropics and sub-tropics due to their large spatial gradients between wet and dry regions.

Recent research has highlighted the importance of radiative forcing from both greenhouse gases and aerosols in driving large-scale shifts in rainfall patterns through their influence on the atmospheric circulation. The instantaneous radiative forcing from greenhouse gases has been shown to drive large-scale changes in the monsoonal circulations. Likewise, the strong hemispheric asymmetry in aerosol radiative forcing has been shown to drive large-scale changes in the meridional circulation. Both of these radiatively-forced circulation changes have direct impacts in modulating the regional distribution of rainfall. Unfortunately, recent studies have highlighted significant biases in model calculations of radiative forcing under identical emission scenarios. Such biases remain largely undocumented since radiative forcing is rarely calculated or archived, despite its fundamental role in determining the forced response to anthropogenic emissions.

Due to their strong influence on atmospheric heating rates, clouds play a key role in regulating the large-scale circulation of the atmosphere and therefore the regional distribution, frequency and intensity of rainfall. Recent studies suggest that regional shifts in rainfall may also be amplified through circulation-driven cloud feedbacks that respond to, and enhance, the radiatively-forced rainfall change. The selection of "*Clouds, Circulation, and Climate Sensitivity*" as one of the **WCRP** Grand Challenges underscores both the importance and current lack of understanding regarding these processes.

This proposal seeks to exploit model simulations from **CMIP6** along with idealized forcing scenarios from **RFMIP** and **PDRMIP** to better quantify and understand the role of instantaneous radiative forcing and cloud-circulation feedbacks in modulating shifts in the spatial distribution and intensity of rainfall.

The primary objectives of this proposal are to:

I. Develop and apply process-oriented metrics to quantify and evaluate model simulations of instantaneous radiative forcing and cloud-circulation feedbacks;
II. Quantify the impacts of radiatively-forced circulation changes on the regional distribution of rainfall;
III. Use historical observations in conjunction with spatial fingerprinting techniques to better constrain the representation of these radiative and cloud processes in models.

In accomplishing these objectives, we will directly contribute to the NOAA MAPP goal of developing and applying process-oriented metrics to better understand sources of model bias involving "cloud and radiative processes" and their impact on "weather and climate extremes".

An Open Framework for Process-Oriented Diagnostics of Global Models

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Abstract

A critical need exists to improve the diagnosis of global climate and forecasting models. For example, models continue to be plagued by common biases in tropical convection and its variability, including well-known trade-offs between the quality of the mean state and of intraseasonal convective variability such as the Madden Julian Oscillation (MJO). A key need is incorporation of process-oriented diagnostics into standard diagnostics packages that can be applied to development versions of the models, allowing the application of diagnostics to be repeatable across multiple model versions. A significant barrier is the lack of a mechanism for getting community-developed diagnostics into the modeling center development process. The proposed work involves close collaboration between diagnostic developers and modeling centers to develop a common and extensible mechanism for rapid dissemination of process-oriented diagnostics across modeling centers. As demonstration of the process, we will implement critical diagnostics for tropical convection and its variability.

Proposed goals will be met as follows:

1) A leadership team with diagnostic developers and software developers at GFDL and NCAR will be formed to develop best practices for implementation of diagnostics into the centers' standard evaluation packages.

2) GFDL and NCAR will coordinate development of a software framework that allows sharing of diagnostics, with an eye to extensibility to other centers (and other diagnostics) during the project lifetime. This coordinated effort will include development of software tools/standards that individual PIs may use to craft their diagnostics into a form easily useable by multiple modeling centers.

3) Initial emphasis will be placed on process-oriented diagnostics related to tropical convection and its variability. The modeling centers have a critical need for diagnostics in this area, making this topic an attractive one for a pilot diagnostics effort. PIs Maloney and Neelin have led development of existing process-oriented diagnostics that will serve as initial test diagnostics for this effort. Continued development of tropical convection diagnostics will also form a key component of the proposed work.

4) The PIs will also coordinate with international efforts that are developing general diagnostics frameworks such as those at PCMDI and the European EMBRACE project, to ensure that the efforts developed here are complementary rather than duplicative of these efforts.

5) This proposal will also provide a mechanism for PIs of the Type 2 proposals funded under this MAPP call to incorporate their new diagnostics into the diagnostics stream of modeling centers. The PIs have developed collaborations with several potential Type 2 PIs at the proposal stage to aid this integration.

Relevance to NOAA: This proposal directly addresses the FFO “MAPP - Process-oriented evaluation of climate and Earth system models and derived projections” by developing a Type 1

core team to lead development of a mechanism for inclusion of process-oriented diagnostics into standard packages of modeling centers, and also conducting scientific development of new process-oriented diagnostics. We will aid NOAA's NGSP by improving models to provide more accurate "assessments of current and future states of the climate system that identify potential impacts and inform science, service, and stewardship decisions."

Understanding Systematic Model Biases in Simulating the Pacific Dynamic Sea Level Variability and Change

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Abstract

Dynamic sea level (DSL) in the Pacific Ocean is an important indicator of climate variability and change. Due to the dominant thermosteric effect, the Pacific DSL reflects the vertically integrated ocean temperature anomalies and temporally accumulated ocean heat uptake/release. Recently, Peyser et al. (2016) identified an east-west see-saw as the dominant variability mode of DSL in the tropical Pacific. This see-saw is closely related to the variability and change of global mean surface temperature. However, climate models tend to show systematic and outstanding biases in simulating this see-saw variability, potentially influencing the accuracy of future climate and sea level predictions and projections.

The primary goal of this project is to investigate the mechanisms responsible for the systematic biases of the new CMIP6 models in simulating the Pacific DSL variability and change, provide strategies and pathways for model development and improvement, and eventually reduce model uncertainty in future climate and sea level predictions and projections. More specifically, the objectives are to: a) analyze observational, reanalysis and modeling data to better understand internal DSL variability and externally forced DSL changes in the Pacific; b) quantify the biases of the CMIP6 models in simulating the Pacific DSL variability and change as well as their climate and coastal impacts, and compare the results with those from CMIP5; and c) use the GFDL high resolution coupled climate models (CM4, CM2.5 and CM2.6) and ocean model (MOM6) to systematically study the sources of the model biases and the critical processes that can lead to model improvement. To achieve the goal, we will perform systematic data analyses and comparison, and conduct a series of sensitivity experiments. We will focus on various critical atmospheric and oceanic processes and identify their roles in causing model biases in simulating the Pacific DSL variability and change.

This proposal is closely relevant to the MAPP competition: Addressing key issues in CMIP6-era Earth system models. The NOAA's long-term goals include improved scientific understanding of the changing climate system and its impacts, and assessments of current and future states of the climate system that identify potential impacts and inform science, service, and stewardship decisions. One focus of CPO's climate research portfolio is on climate intelligence which includes observations, modeling and prediction. We anticipate that the outcome of this project will meet NOAA's goals by deepening our understanding about the causes of the Pacific DSL variability and change and the mechanisms for systematic and outstanding model biases, thereby helping reduce model uncertainty and leading to more accurate climate and sea level predictions and projections including extreme events. During the project, the PIs will closely interact with the CMIP, FAFMIP and OMIP modeling communities and contribute to the related IPCC assessments.

Weather-type based cross-timescale diagnostics of CMIP6-era models

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Abstract

The objective of this project is to perform a process-based multi-timescale diagnostic of CMIP5 and CMIP6-era Earth System Models using a weather-typing dynamical approach. The proposed work focuses on how accurately extreme rainfall events, both wet and dry, are represented over the US in CMIP5/6 models. Although the project will emphasize the present and next generation of NOAA/GFDL models, to guarantee robustness other available models will also be diagnosed.

This project will develop process-informed cross-timescale tools to diagnose CMIP5/6 historical and climate-change projections over North America based on the methodology of large-scale recurrent, persistent weather types (WTs), also known as large-scale meteorological patterns (LSMPs). These regimes provide a dynamically informative intermediary between the largescale drivers of climate variability and change from sub-seasonal to decadal timescales, and midlatitude high-impact weather events, through the mechanism of synoptic control. The proposed work will provide an urgently-needed process-level understanding on rainfall extremes in CMIP5/6 simulations, and develop standard metrics that model developers and users can apply to these models easily. These will allow model developers to quickly assess the impacts of changes in parameters, and will enable users to better assess confidence levels on projections of return intervals of extreme rainfall events.

The proposed work will build on recent previous work by the team demonstrating the effectiveness of the approach to both (1) cross-timescale diagnostics of rainfall over North and South America, and (2) diagnose GCM model performance in a suite of GFDL forecast models. Expected deliverables of the project include (a) general open-source software package to perform weather-type based cross-timescale diagnostics of climate models, including new process-based metrics that can be added to the MAPP diagnostics Task Force framework, and documentation for the software package; and (b) an online “diagnostic atlas” containing the process-based metrics (e.g., WT spatial patterns and frequencies of occurrences at different timescales, extreme rainfall composite analysis for different thresholds, anomaly correlations to climate drivers) available via the IRI Data Library.

Process-oriented Model Evaluation for the North American Monsoon

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Abstract

The objective of this proposal is to develop process-oriented diagnostics to evaluate global model representation of the North American monsoon (NAM) and explore the pathways to model improvements. The NAM is chosen to be the focus of the project because of its significance to the United States, and also because it serves as an ideal testing ground for model evacuation and improvement owing to the important roles of many fundamental physical processes and their interplay with the large-scale monsoon circulation. We will focus three aspects of the NAM, its moist thermodynamic perspective, the link between the continental monsoon to the subtropical northeastern Pacific cloud regime, and the multi-scale nature of the NAM. Process-oriented diagnostics will be developed in the convective quasi-equilibrium framework to evaluate the seasonality, structure, intensity and variability of the NAM. The simulated convection and cloud processes will be evaluated using satellite and site-specific data from the ob4MIPs. In particular, the synergetic analysis of the CloudSat and MODIS will help to link the deficiencies in simulated cloud processes to uncertain parameters in microphysics schemes. In addition, two bulk metrics, which link model performance and physics formulation, will be tested and are expected to provide insights into model improvement. Although we focus on the NAM, the proposed research addresses some common issues in climate models and will contribute to improvement of the overall model performance.

The GFDL models (CM4, AM4 and fvGFS) will be employed to assist the development and testing of the diagnostics and metrics. Perturbed-physics ensembles will be carried out using CM4 and AM4 in the weather forecasting mode, and the high-frequency output will be evaluated to examine fast-physics error growth and constrain parameter uncertainties based on observations. Climate simulations will be further carried out to examine slow error growth. In addition, the fvGFS will be run at the seasonal-prediction mode with a configuration similar to the GFDL fvGFS experimental 10-day forecasts (i.e., 13-km globally uniform resolution with an interactive, refined grid of 3-km resolution). These simulations will be used to assess climate model errors, especially in representing multi-scale processes and weather/climate extremes. The simulations will also help to explore the capability of the fvGFS in seamless prediction from the synoptic to the seasonal time scales. The diagnostics and metrics will be developed and tested mainly using the GFDL model simulations, and further testing of robustness will be carried out using the CMIP6 data, in particular the CFMIP, GMMIP and HighResMIP.

The proposed research falls right into the focal area of the MAPP's competition on "addressing key issues in CMIP6-era earth system models", and is also highly relevant to the MAPP's mission to enhance the Nation's capability to predict natural variability and changes in Earth's climate system.

Process-Based Evaluation of the Representation of Lake-Effect Snowstorms in the Great Lakes Region Among CMIP6 Earth System Models

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Abstract

The vast socio-economic importance of the Great Lakes cannot be understated. They contain 95% of the U.S.' freshwater supply and impact power production, navigation, industry, commerce, recreation, agriculture, and ecosystems. Their basin has been a regional hotspot of pronounced climate change impacts, including rising air temperatures, more frequent heavy precipitation events, rapid summer warming of lake surfaces, declining lake ice cover, enhanced lake evaporation, and increase in lake-effect snowfall. Extreme weather events have drawn increased attention, due to their acute societal impacts, improved modeling capabilities, and climate change concerns. While the Intergovernmental Panel on Climate Change (IPCC) reports and National Climate Assessments summarize existing research on extreme events, they give minimal attention to lake-effect snowstorms, despite their dramatic socio-economic and environmental impacts. It remains unclear how the frequency of these cold season extremes will change during this century. The insufficient investigation of projected changes in these cold season extremes is partly due to the general lack of suitable modeling tools that properly represent the Great Lakes and associated lake-atmosphere interactions, at a sufficient spatial resolution. The CMIP6 High Resolution Model Intercomparison Project (HighResMIP) represents an unprecedented multi-institutional effort to generate global simulations down to a median resolution of 30 km and a unique opportunity to assess the capability of high-resolution GCMs to accurately represent lake-atmosphere interactions and resulting lake-effect snowstorms. A process-based evaluation is proposed of the representation of lake-atmosphere interactions and resulting lake-effect snowstorms in the Great Lakes region among CMIP6 Earth System Models. Analysis will primary focus on HighResMIP runs and their likely advances over coarse DECK historical runs. Analyzed observational datasets will include: station snowfall from NCDC and Environment Canada; CloudSat and Global Precipitation Measurement cloud/snowfall estimates; wind, temperature, and sea-level pressure from North American Regional Reanalysis; Great Lakes Evaporation Network over-lake evaporation and turbulent flux measurements; buoy water temperature, air temperature, and wind from National Data Buoy Center; Great Lakes Surface Environmental Analysis lake-surface temperature; Great Lakes Environmental Research Laboratory (GLERL) vertical lake temperature data; GLERL lake ice thickness; over-lake precipitation, lake evaporation, and drainage basin runoff from GLERL Great Lakes hydrologic dataset; and NOAA Great Lakes Ice Atlas. The following meteorological and limnological variables, considered as essential mechanistic ingredients in lake-effect snow forecasting, will be evaluated in HighResMIP runs in terms of lake-effect snowfall occurrence and intensity: temperature difference between the lake surface and 850-hPa; direction and speed of the sub-700-hPa steering wind; lower tropospheric vertical directional shear of the steering wind; existence, height, and strength of a low-level subsidence inversion; over-lake vapor pressure gradient; and lake ice cover. The study is highly relevant to MAPP competition objectives of addressing key issues in CMIP6 ESMs in terms of climate extremes, through the design and application of process-oriented metrics for evaluating and improving the representation of lake-atmosphere interactions and resulting lake-effect snowstorms in CMIP6 models. The project addresses NOAA's goals to attain "improved...understanding of the

changing climate system” and perform “assessments of current and future states of the climate system that identify...impacts and inform...decisions.